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STABILITY RELATIONSHIP FOR WATER DROPLET CRYSTALLIZATION

WITH THE NASA LEWIS ICING SPRAY NOZZLE

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Abstract

In order to produce small droplets for icing cloud simulation, high-pressure air-atomizing nozzles are used. For certain icing testing applications, median drop sizes as small as 5 μm are needed, which require air-atomizing pressures greater than 3000 kPa. Isentropic expansion of the ambient temperature atomizing air to atmospheric pressure can result in air stream temperatures of -160 °C which results in ice crystals forming in the cloud. To avoid such low temperatures, it is necessary to heat the air and water to high initial temperatures. An icing spray research program was conducted at AEDC to map the temperatures below which ice crystals form. A soot slide technique was used to determine the presence of crystals in the spray.

Introduction

Refurbishment of the Lewis Altitude Wind Tunnel (AWT), proposed for completion in the early 1990's, was planned to include the capability of conducting icing research along with aerodynamics, propulsion and acoustic studies. Since ice accumulation on aircraft and engine surfaces can seriously degrade performance, icing tests are an important aspect of the development and verification tests of aerospace flight systems. The ultimate goal of a ground based test facility is to effectively simulate icing conditions actually encountered by an aircraft in flight.

To simulate natural icing clouds in a wind tunnel, water droplets are injected into the air stream through an air-atomizing nozzle. The size of the droplets may be varied by controlling the atomizing air pressure. An icing cloud encounter is properly simulated by regulating the ambient air temperature and velocity, the water droplet size and the liquid water content (LWC) in the air stream.

To produce small droplets for icing cloud simulation high-pressure air-atomizing nozzles are used. For certain icing test applications, such as model scaling, median drop sizes down to five microns are needed which may require air-atomizing pressures greater than 3000 kPa. Isentropic expansion of the atomizing air from this pressure to atmospheric pressure results in air stream temperatures of -160 °C which will result in ice crystals forming in the cloud unless the air and water are heated to high initial temperatures. An example of the effect of low atomizing air temperatures is shown in Fig. 1 from Ref. 1. Below an air atomizing temperature of 61.7 °C, the accreted ice shape was considerably reduced and significantly different. At an air atomizing temperature of 21.1 °C no ice accreted at all, possibly because all the droplets were frozen. This was for one tunnel temperature and atomizing pressure. A complete transition map was desired.

In early research the degree of supercooling for single droplets has been studied. For example, Heverly[2] supported droplets on wax paper or on a thermocouple. He showed that droplets could be supercooled to -33 °C. The smallest droplet that he used was 50 μm in diameter. He also found that the degree of supercooling decreased as the drop size increased. His data showed that the spontaneous freezing point was independent of the cooling rate and pressure.

Dorsh and Hacker[3] studied small drops supported on platinum or copper plates. They found that droplets of a given size froze over a range of temperatures of ±4 °C for drops less than 25 μm, and ±10 °C for drops 50 μm or larger. Bigg[4] suspended the drops between immiscible fluids or on a layer of hydrophobic silicon oil (Drifilm). He found that the freezing temperature varied as the logarithm of the diameter. Data taken by Bigg show lower freezing temperatures than those found by researchers using solid surfaces.

Kuhns and Mason[5] photographically measured the freezing of falling drops and determined the droplet size from the terminal velocity. Their results agreed closely with the work of Bigg.

It is difficult to relate single droplet behavior to the characteristics observed in water droplet sprays. Previous studies have dealt primarily with individual droplets that are slowly cooled (0.3 °C/sec). This report addresses the rapid supercooling of sprays. Droplets within a spray interact with the continuously changing temperature and velocity of the atomizing air stream. The atomizing air stream flows from the nozzle as an overexpanded jet at low temperatures and high velocity. The spray interacts with the atomizing air and both streams mix with the ambient air in a continuously changing environment. To determine whether freezing (crystallization) will occur, studies must be conducted using the actual spray configuration.

In an icing cloud the droplets exist in a liquid state supercooled below their normal freezing point (0 °C). Lazelle[6] used an air atomizing spray and collected the droplets on oil slides. He showed that under some conditions in wind tunnel testing, the water droplets crystallized if the temperature of the atomizing air was sufficiently low. Preliminary data taken at the Lewis Research Center in the Icing Research Tunnel (IRT) showed that by lowering the nozzle air and water temperatures from 80 to 35 °C, where droplet crystallization might occur, the ice that formed on the model was quite different from ice that was formed at normal test conditions, see Fig. 1.

The purpose of these tests was to determine the effect of: (i) atomizing air temperature and pressure on the formation of ice crystals, (ii) ice crystals on ice accretion shapes, and (iii) tunnel conditions on median drop size and size distribution. The tests reported herein were conducted at the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC). The user/sponsor was NASA Lewis. Tests were conducted at a tunnel Mach number of 0.3 and tunnel temperatures of -13 and -8 °C. The liquid water content was approximately 0.6 gm/m^3.

Facility

The tests were conducted in the single nozzle icing spray facility shown in Fig. 2. The air flow rate is measured using a critical flow venturi and water droplets are sprayed into the primary air stream through a single two-phase atomizing spray nozzle located in the plenum chamber upstream of the bellmouth. The bellmouth terminates in a 30.5 cm diameter duct that directed the free jet of conditioned air into the 0.91 m diameter test section. A secondary air system supplies air into the test section to prevent recirculation of the water droplets into the expansion. The distance from the nozzle to the measuring station is 4.42 m.

During the test, the drop size distribution was determined with the Laser Fiber Optic System (FOS). The FOS uses a single laser beam and measures the shadow of the particle with a lens system and row of photomultiplier tubes. The system assigns each droplet to one of thirty bins, each representing a different droplet size. Each bin width is 2.778 μm in diameter and sizes from 5 to 100 μm are included. The data is automatically recorded and reduced to produce volume median drop sizes and drop size distributions. The system averages from 5000 to 15 000 drops per reading.

A "soot slide" technique as described by Skidmore and Pavia[7] was used to indicate the presence of crystals. The impressions of the droplets in the soot coating are indicative of the state, liquid or crystal, of the water droplets. The technique was chosen because of its simplicity and economy of operation. A slide could be exposed, withdrawn, examined, and a new slide inserted in approximately 15 min without shutting down the tunnel. In this technique, small plexiglass slides were coated with kerosene lamp soot and then briefly exposed to the air stream at the measurement station. The slide was 0.635 cm wide by 3.81 cm long and 0.32 cm thick. The slide was inserted into a 2.54-cm diameter probe and exposed by a rotating slot shutter, Fig. 3. A copper cap with a 0.32 by 2.54 cm slot was rotated rapidly by a hand crank to expose the soot slide. The soot slide holder could be removed from the probe without removal of the mechanism from the test cell or shut down of the test cell. The sampling mechanism was purged with hot air between data points to prevent excessive ice buildup on the sampling cap. A picture of the disassembled soot slide probe is shown in Fig. 4.

The NASA Lewis standard icing spray nozzle is shown in Fig. 5. This nozzle was selected for use in the AWT because it has been extensively calibrated and is currently used in the Lewis Icing Research Tunnel. Since the atomizing air was introduced at a pressure above the choked condition of the nozzle, the water jet was introduced to an expanding supersonic air stream. The resulting atomizing air stream temperature was well below the homogeneous freezing point of the spray for a short period of time until the ambient tunnel air was entrained into the stream.

Results

The effect of atomizing air temperature on droplet crystallization was evaluated by setting the atomizing air pressure between 300 and 830 kPa and lowering the atomizing air temperature from 115 to 15 °C. Tests were conducted at tunnel temperatures of -13 and -8 °C. Most of the tests were conducted at a spray nozzle water temperature of 60 °C. The tunnel Mach number was 0.3 and the liquid water content (LWC) was 0.6 gm/m^3. At a LWC of 1.2 the shutter on the probe could not be manually moved fast enough and most of the soot was washed off the slide.

The tunnel and spray conditions were set and a soot slide was exposed and examined under the microscope for the presence of crystals. In most tests a second slide was exposed for verification because the probe was operated manually and sample quality varied. If most of the droplets were observed to be crystallized on a slide, the point was marked below the transition. Then the air temperature was raised and another data point was taken. The process was repeated at various pressures until a transition line could be established. Selective photos of the soot slides will be discussed later.

The stability map for droplet crystallization is shown in Fig. 6. The lines are drawn through the transition where crystals were predominant on the slide. For a given ambient air temperature as the air pressure is increased the atomizing air temperature must also be increased to prevent crystallization. Lazelle's[6] data at -33 and -20 °C are shown as short dashed lines. Lazelle had a "rule of thumb" shown by the solid line that the nozzle air temperature in degrees centigrade should be greater than twice the nozzle air pressure in psig. The -13 and -8 °C lines are shown extended above 100 °C indicating that data was taken at conditions where the air temperature had to be heated above the boiling point of water to prevent crystallization after expansion of the atomizing air.

The drop size is shown as a subscale on the figure. The median drop size as measured by the FOS instrument did not change, within experimental deviation, with changes in air temperature. Even on crystallization the FOS system did not indicate changes in drop size. In mapping out the two curves, 104 soot slides were taken and 127 FOS laser readings were recorded.

The effect of atomizing air pressure on drop size distribution is seen from the soot slide impressions, shown in Fig. 7. At these conditions no crystals were present. Because the probe was manually activated, the time of exposure was not constant. As the pressure is increased the drop size is significantly reduced. These photos were produced by placing three slides directly on a 35 mm photoenlarger and exposing a 20 by 25 cm (8 by 10 in.) print. The 0.635 wide slide is magnified about ten times. The round dark circles are craters in the soot where droplets have hit. When the droplets hit, they flatten and leave an impression larger than the size of the drop. Skidmore and Pavia[7] give a calibration of soot slide image size versus drop size; their calibration is presented in Fig. 8. The ratio of drop size diameter to impression diameter is a strong function of impact velocity. Above 200 m/sec droplet breakup may occur on impact. When this occurs multiple small images may appear. All the tests reported here were made with a Mach number of 0.3 (100 m/s). At this velocity, Fig. 8 shows that the soot-slide image is 5 times larger than the spherical drop diameter.

The dropsize distribution as determined from the laser FOS system is shown in Fig. 9. The distribution peaks at 10 μm for the three sprays. As the atomizing air pressure decreases the number of large drops increases, which increases the volume median drop size. In this work no attempt was made to determine the volume median drop sizes from the soot slides to compare with the laser FOS measurements. The largest drop size that the laser FOS system can measure is 90 μm so that some of the larger drops that might be present at low pressure could not be measured.

The effect of atomizing air temperature on the degree of crystallization is seen from the soot slide images shown on Fig. 10. As the temperature is reduced streaklines appear showing the motion of the frozen particles in the soot. The streaklines might be created by frozen ice balls rolling in the soot. The lines are present on both sides of the stagnation line of the slide. On Fig. 10(b) only a few streaklines are present, whereas on Fig. 10(c) the slide is covered. Therefore it was concluded that the crystallization temperature was midway between the two conditions at 63 °C.

By looking at the slides under a microscope further magnification is obtained. The overall magnification is 100 for Figs. 11 and 12. Figure 11(a) shows that the unfrozen droplets produce circular images on impact. As the tunnel temperature is lowered, the freezing droplets leave an irregular impression on the soot slide. It is difficult to determine whether the smaller droplets in Fig. 11(b) are frozen. Definite crystalline dendrites are present in Fig. 11(b) indicating the condition of crystals being present.

One question is where does the phase transition take place: in the air or on the soot slide? There is no doubt that the soot particles on the slide could act as nucleation sites if conditions are right. However, freezing would have to occur in less than 0.2 μs to prevent a liquid impact image from forming. This time is based on the droplet diameter over the velocity of the drop. Observation of single droplets suggests that freezing cannot occur this quickly. It will also be shown that the ice accreted on a model is significantly different when an icing test is run with atomizing air temperature below the crystallization limit shown in Fig. 6 and that it is important to stay above this limit for proper simulation of a supercooled cloud. Therefore one concludes that crystallization has occured before impact with the slide. An additional consideration is that if nucleation was triggered by the soot, transition would be at a higher atomization air temperature than a soot free surface. Therefore the results of this report would be a conservative estimate of transition.

The determination of whether crystals are present is subjective. Figure 12(a) shows a slide taken at conditions for which crystallization would not be expected. It is seen that the larger droplets contains some irregularity, suggesting that crystals have formed, around the outer edge, but the small ones appear round, suggesting they are not frozen. Even under further magnification the smaller images are round. At the higher atomizing air pressure of 820 kPa crystallization was present even when the atomizing air temperature was above the boiling point of water at 110 °C, Fig. 12(b). The drop size as measured by the laser FOS system did not show any change in size when the atomizing air temperature was raised above the boiling point of water.

A sequence of tests was made to determine if the ambient air temperature affected the drop size. Extensive dropsize data have been obtained at room temperature conditions and it was important to determine its applicability at icing temperatures. The atomizing air was heated to control the density and mass flowrate at a given pressure. The data is shown in Table 1. The data is ordered in increasing air pressure. Four nozzle conditions were tested. Within the scatter of the data there was no effect of tunnel temperature.

In an attempt to relate the stability curves to the static temperature of the atomizing air jet, it was assumed that the atomizing air expands to the tunnel pressure isentropically. Using the isentropic expansion relationship:

$$T_o = T_s\left(\frac{P_o}{100\ \text{kPa}}\right)^{\gamma-1/\gamma} \tag{1}$$

and plotting lines of constant static temperature on the stability map, Fig. 13, one observes that the lines have very nearly the same slope as the experimental curves. As the atomizing air mixes with the ambient tunnel air, the droplets are exposed to a varying air temperature. The actual temperature history is complicated, and the droplet may possibly travel through shocks which form at the nozzle exit. Actual shock and flow calculations were attemped with a two dimensional Euler code but the calculations were unstable and the solution diverged. In addition the effect of droplets on shock conditions were not known. Examination of Fig. 13 shows that the crystallization temperature is strongly related to the initial sink temperature of the atomizing air.

Figure 14 is the relationship between the ambient temperature and the static temperature of the atomizing air after expansion which leads to crystallization. It was obtained by cross-plotting the four nearly coincident lines of Fig. 13 of the ambient temperature and the corresponding atomization stagnation temperature. At an ambient temperature of -8 °C an initial static temperature of -75 °C could be tolerated. The actual mixing process is complicated. At a given atomizing pressure, as the ambient temperature is reduced the initial atomizing air temperature must be increased to prevent crystals from forming. Also shown on this figure are the ice accretion test points for the ice shape data of Fig. 15.

The stabilization curves were established on tests that were conducted at a initial water temperature of 60 °C. A limited number of soot slide tests were made at a water temperature of 38 °C which showed that the crystallization point was nearly the same and therefore not a strong function of the initial water temperature.

The change in ice shape on a 2.54 cm diameter pipe with the presence of crystals in the spray is shown in Fig. 15. At the lower atomizing air temperature where the droplets have crystallized, Fig. 15(c), the horns have not formed and the catch is considerably reduced. Good agreement with the stability curve shown on Fig. 14 is obtained. Figure 15 indicates that the presence of crystals in the spray does significantly affect the ice shape formed. The data of Fig. 15 are very similar to the airfoil data of Fig. 1, indicating a decrease in ice accretion at the transition temperature.

Conclusions

The results of this study validate the concern over droplet crystallization, define the spray nozzle operating conditions at which droplet crystallization occurs, and show that the resultant ice shapes on test models vary significantly if the droplets are crystallized. At high atomizing pressures, atomizing air temperatures above the boiling point of water are required to prevent crystallization. The stability curve is related to the static temperature curves of the atomizing air jet. Within the scatter of the data there was no effect of tunnel temperature on median drop size. Even if the soot produced initial nucleation, the data of this report would represent a conservative estimate of the transition temperature. The data will be beneficial in the design of water droplet injection systems to effectively simulate icing clouds in wind tunnel testing.

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TABLE 1. - EFFECT OF TUNNEL TEMPERATURE ON DROP SIZE

[Air atomizing temperature = 82.9 °C

water temperature = 63 °C.]

Tunnel temperature, °C	Atomizing air pressure, kPa	Water pressure, kPa	Drop size, μm
19.50	310.	439.	24.
-7.11	311.	441.	21.2 20
20.50	448.	541.	13.0 12.3
-1.61	453.	546.	12.5 12.4
-2.17	448.	543.	12.6 11.7
-6.89		538.	12.4 12.4
-7.05		538.	12.6 11.7
20.55		1503.	29.6 30.2
-7.11		1503.	27.6 30.5
20.50	830.	856.	7.6 7.5
-2.78	828.	841	7.4 7.0
-6.94	828.	848	7.4 7.7

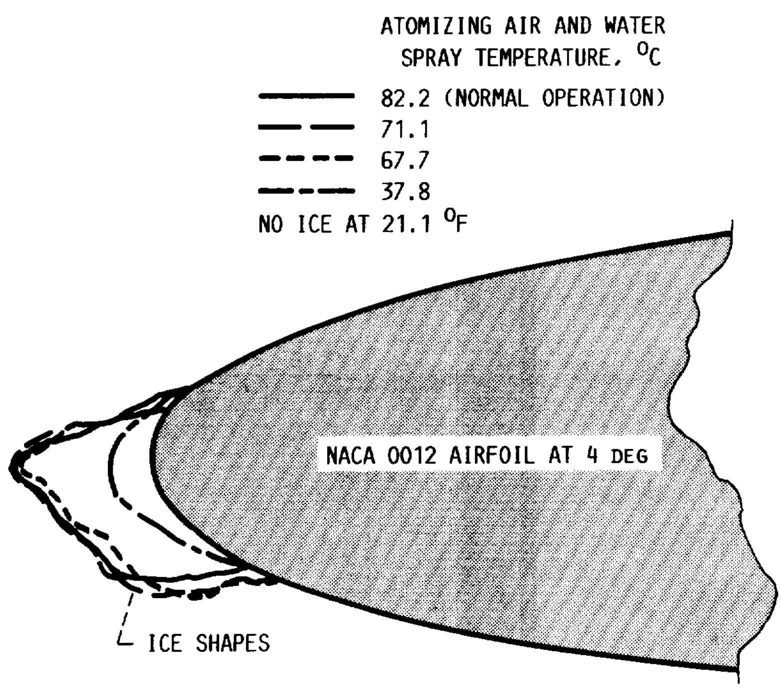

FIGURE 1. - EFFECT OF SPRAY TEMPERATURE ON ICE ACCRETION, REF. 1. SPRAY PRESSURE: P_{AIR} = 408 KPA; P_{H_2O} = 544 KPA; DVM, 15 μM; LWC, 0.8 G/M^3; AIR TEMPERATURE, -12.2 °C; AIRSPEED, 92.6 M/SEC.

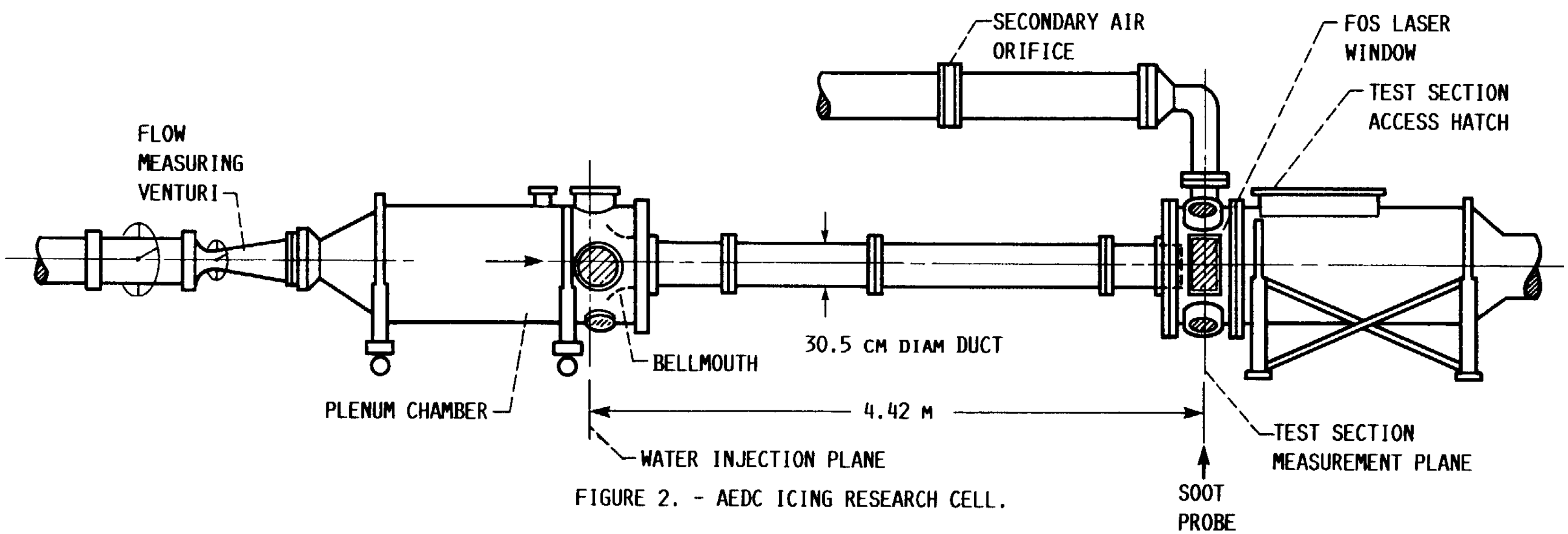

FIGURE 2. - AEDC ICING RESEARCH CELL.

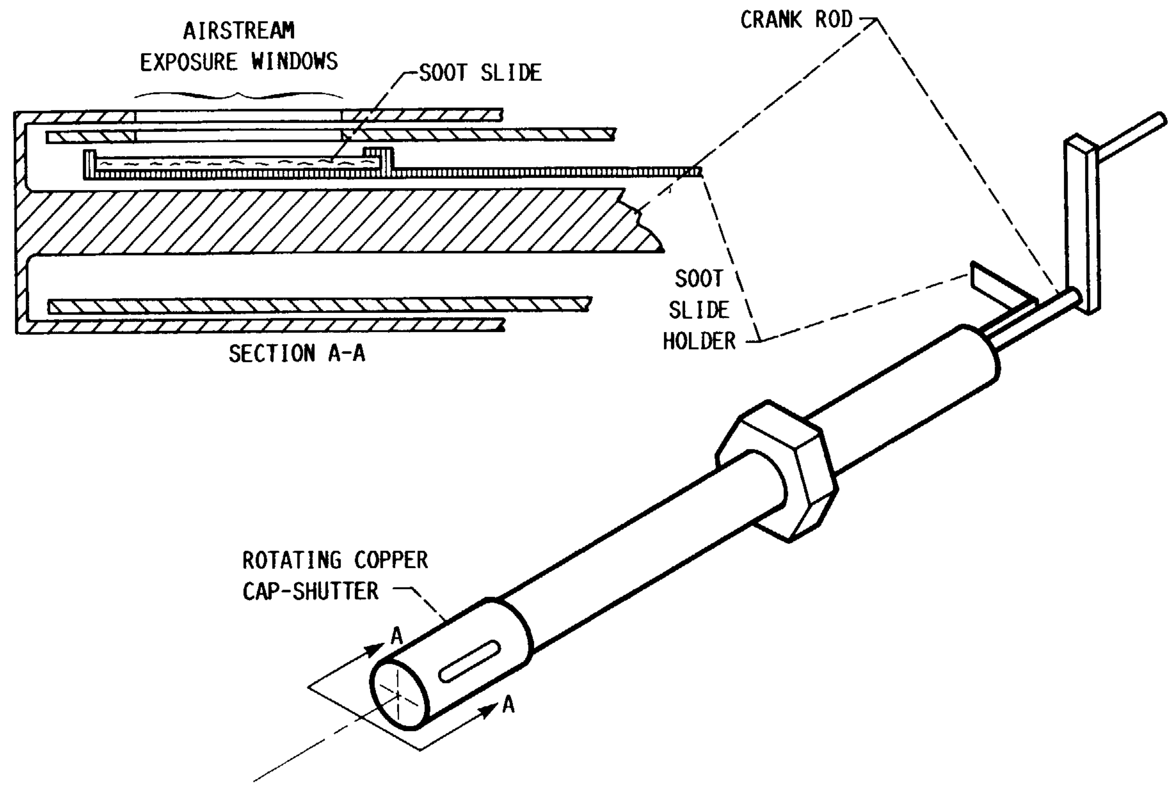

FIGURE 3. - SAMPLING MECHANISM.

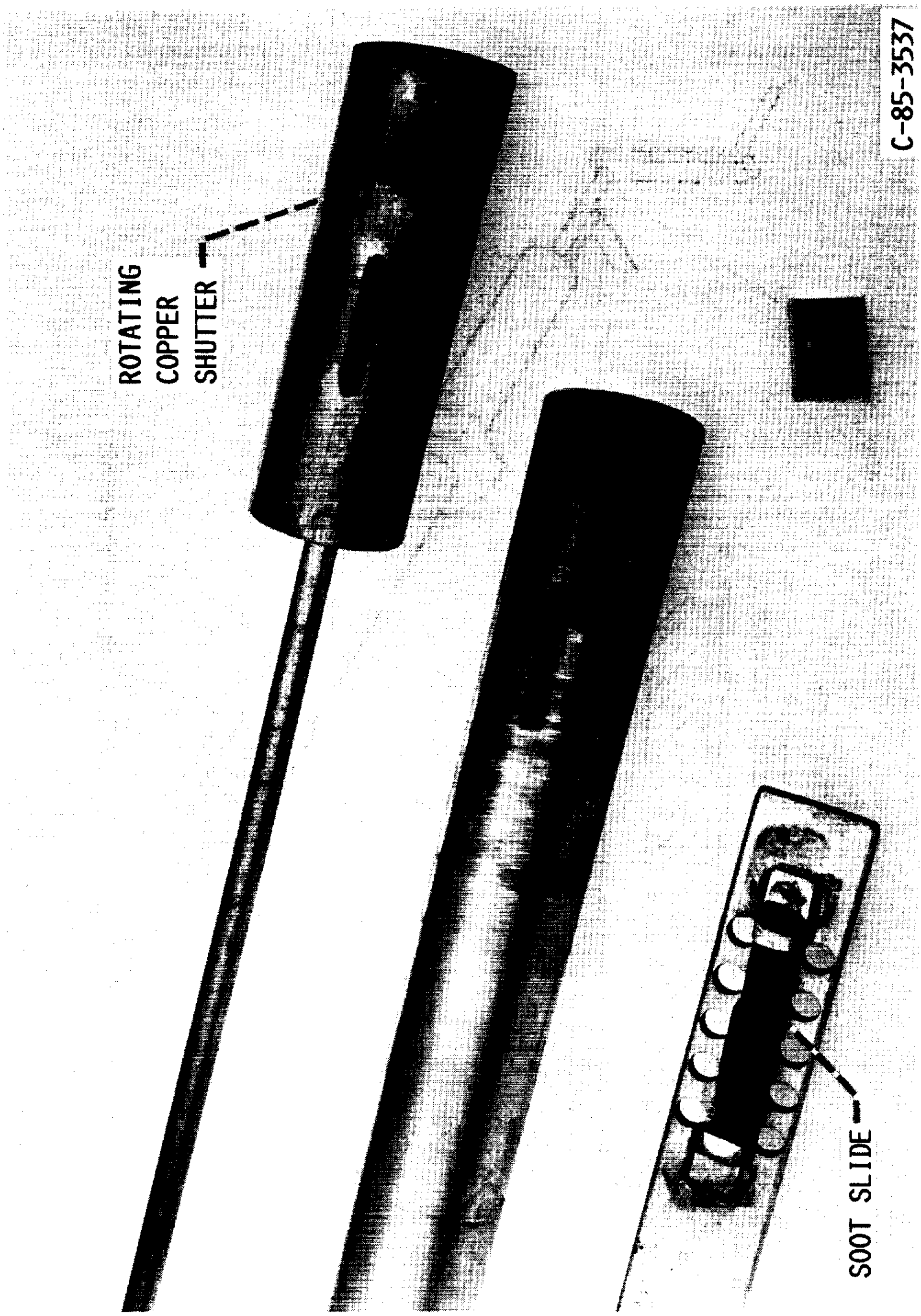

FIGURE 4. - DISASSEMBLED SOOT SLIDE PROBE.

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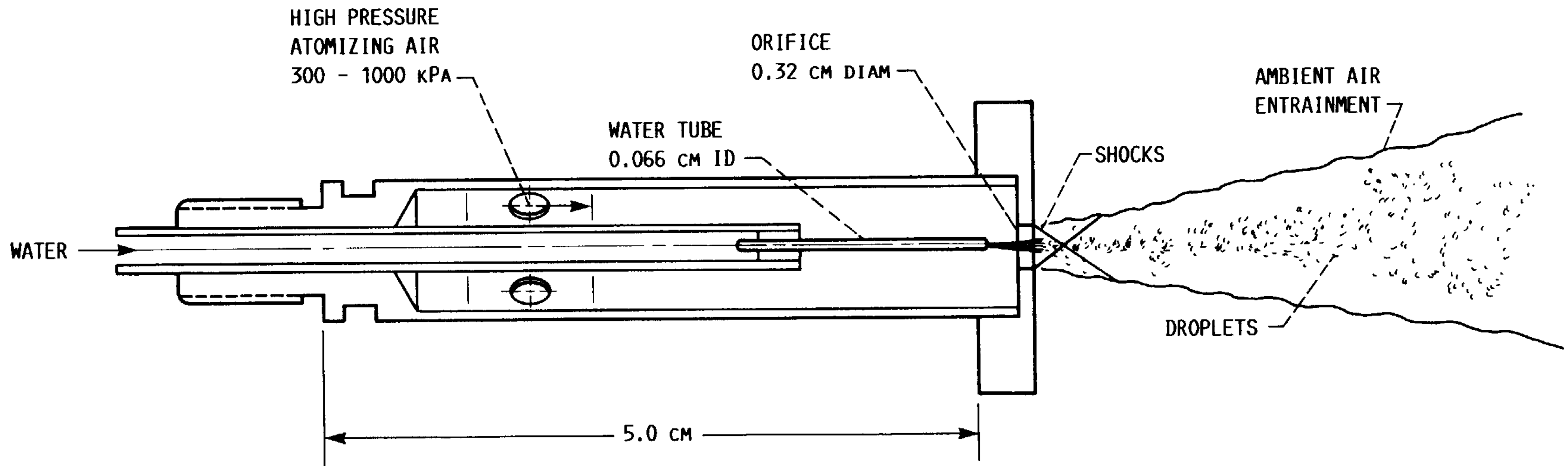


FIGURE 5. - NASA-LEWIS STANDARD ICING SPRAY NOZZLE.

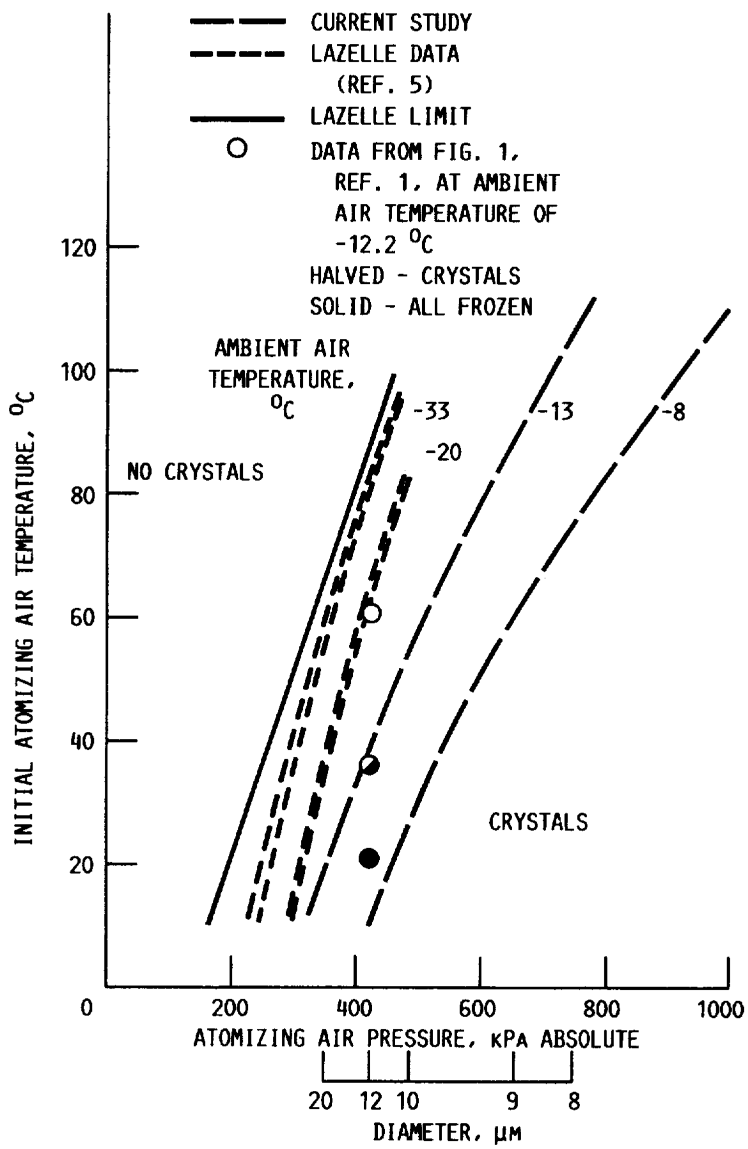


FIGURE 6. - STABILITY MAP FOR THE OCCURRENCE OF DROPLET CRYSTALLIZATION.

(A) ATOMIZING AIR PRESSURE, 650 kPa. DROPLET DIAMETER - 8.7 μm; WATER PRESSURE = 700 kPa.

(B) ATOMIZING AIR PRESSURE, 450 kPa. DROPLET DIAMETER = 12.0 μm; WATER PRESSURE - 535 kPa.

(C) ATOMIZING AIR PRESSURE, 310 kPa. DROPLET DIAMETER = 21.1 μm; WATER PRESSURE = 435 kPa.

FIGURE 7. - EFFECT OF ATOMIZING AIR PRESSURE ON SOOT SLIDE IMAGES. TUNNEL AMBIENT TEMPERATURE - 8 ^{o}C, ATOMIZING AIR TEMPERATURE - 82 ^{o}C.

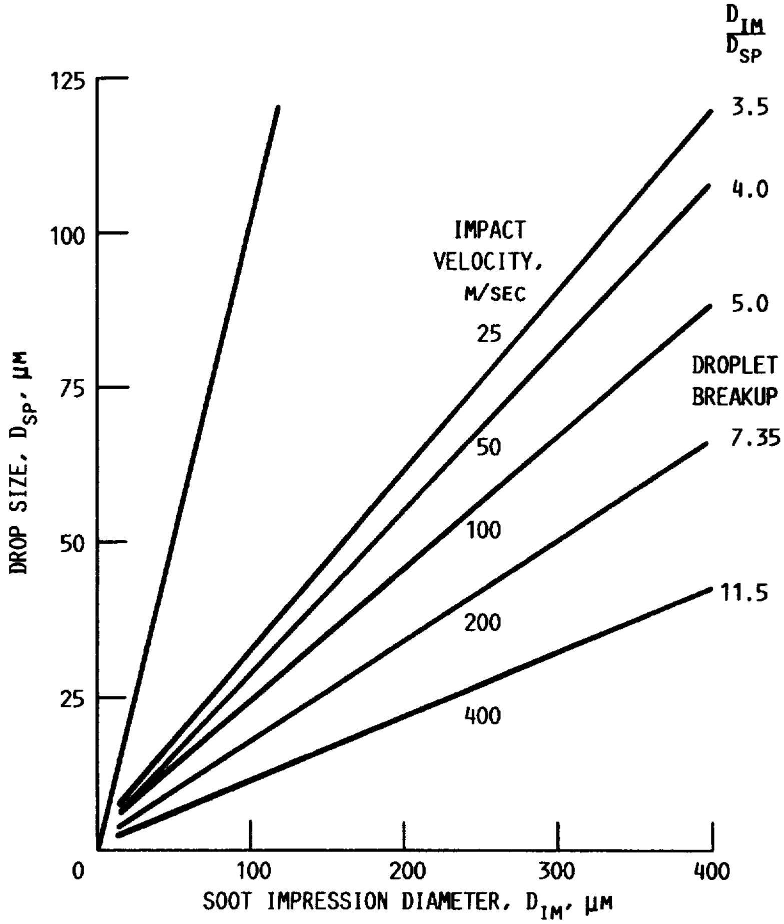


FIGURE 8. - DROP SIZE VERSUS SOOT IMPRESSION SIZE, ADAPTED FROM REF. 7.

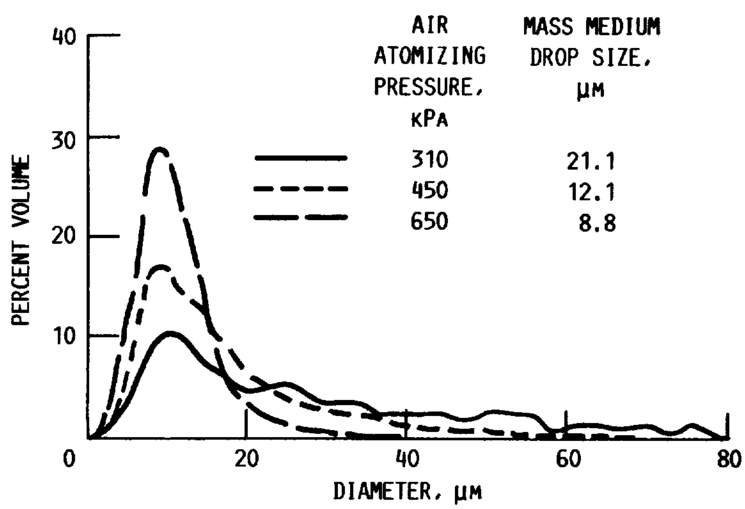
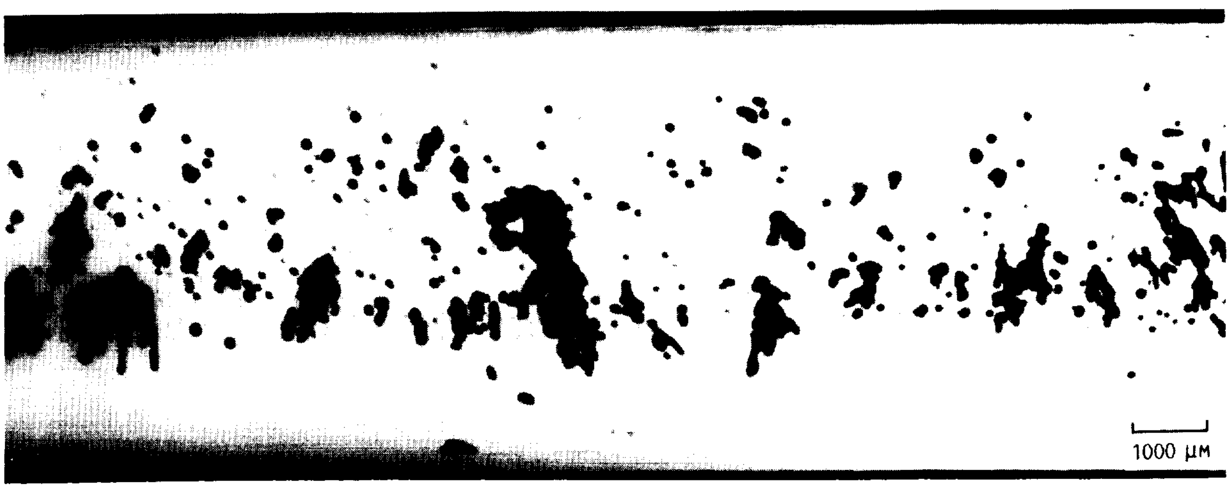


FIGURE 9. - DROP SIZE DISTRIBUTION AS MEASURED BY THE FOS SYSTEM.

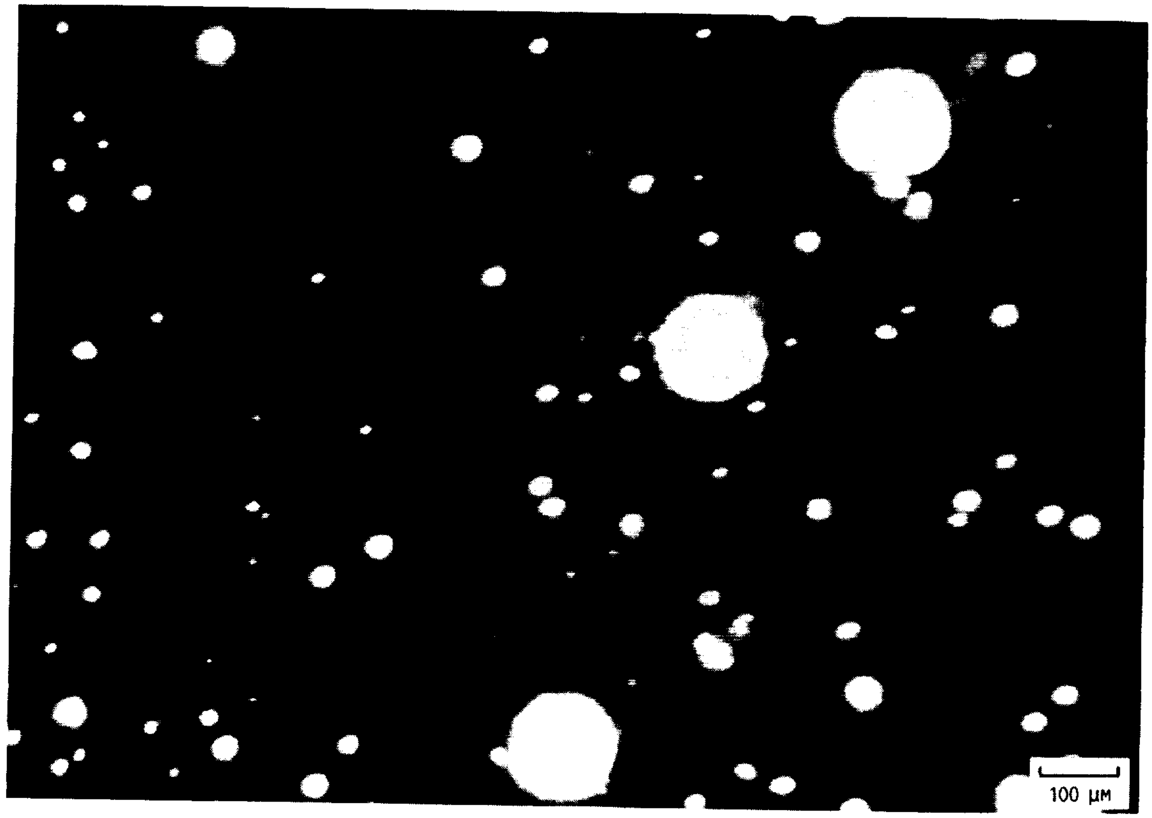
(A) ATOMIZING AIR TEMPERATURE, 71 ^{o}C.



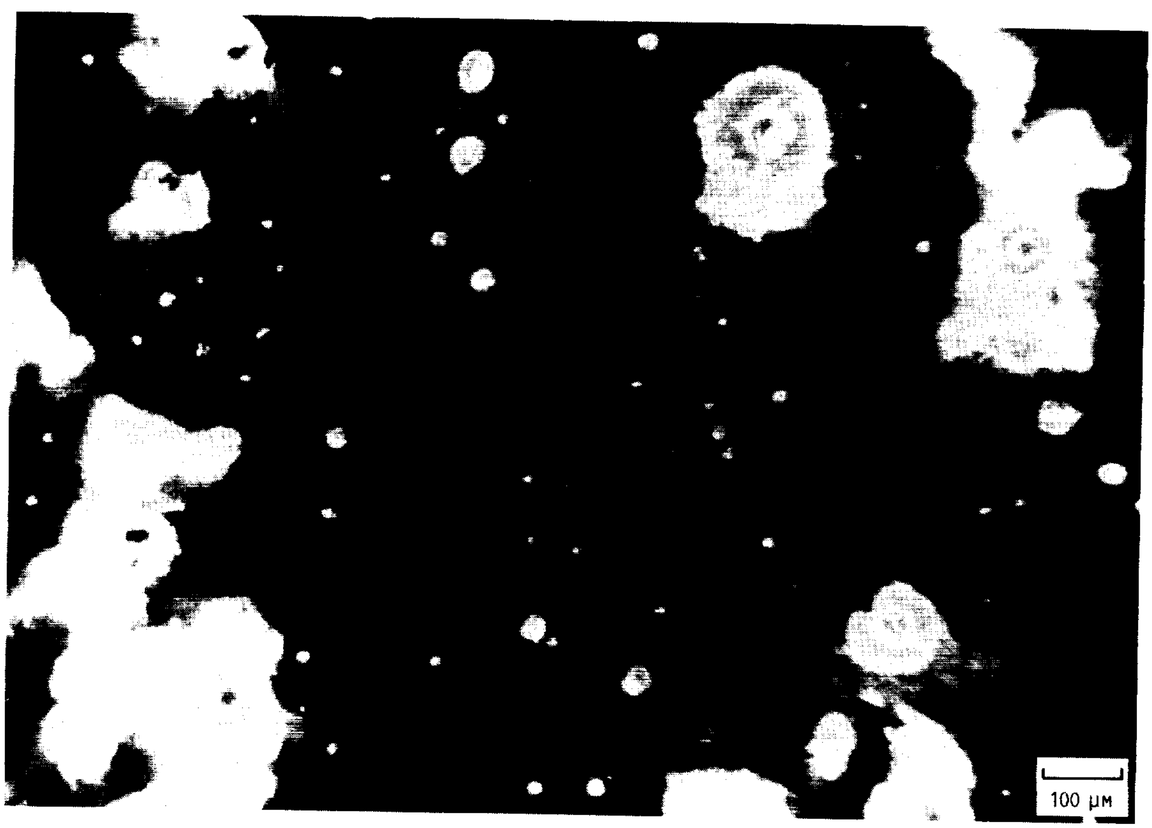
(B) ATOMIZING AIR TEMPERATURE, 65.5 ^{o}C.

(C) ATOMIZING AIR TEMPERATURE, 60 ^{o}C.

FIGURE 10. - EFFECT OF ATOMIZING AIR TEMPERATURE ON SOOT SLIDE IMAGES. TUNNEL AMBIENT TEMPERATURE - 8^{o}C, ATOMIZING AIR PRESSURE 650 KPA, DROPLET MEDIAN DIAMETER - 8.7 μM

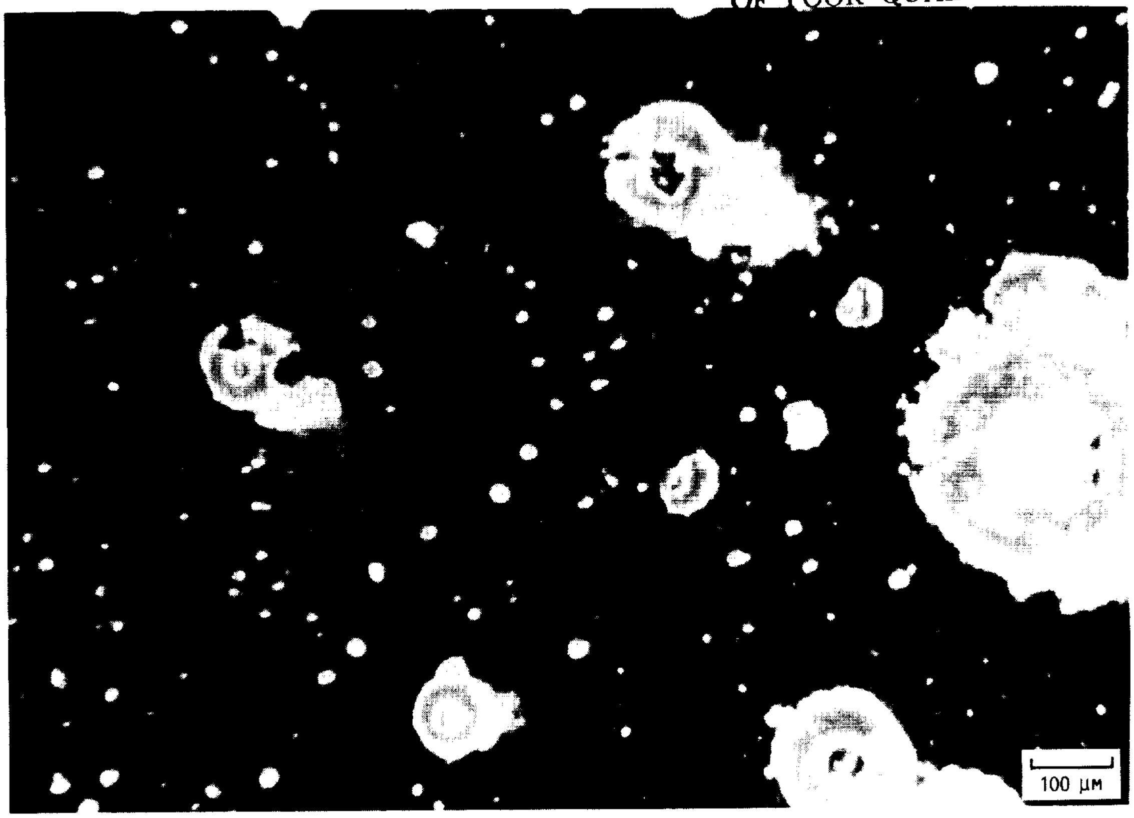


(A) TUNNEL AMBIENT TEMPERATURE - 8 ^{0}C.

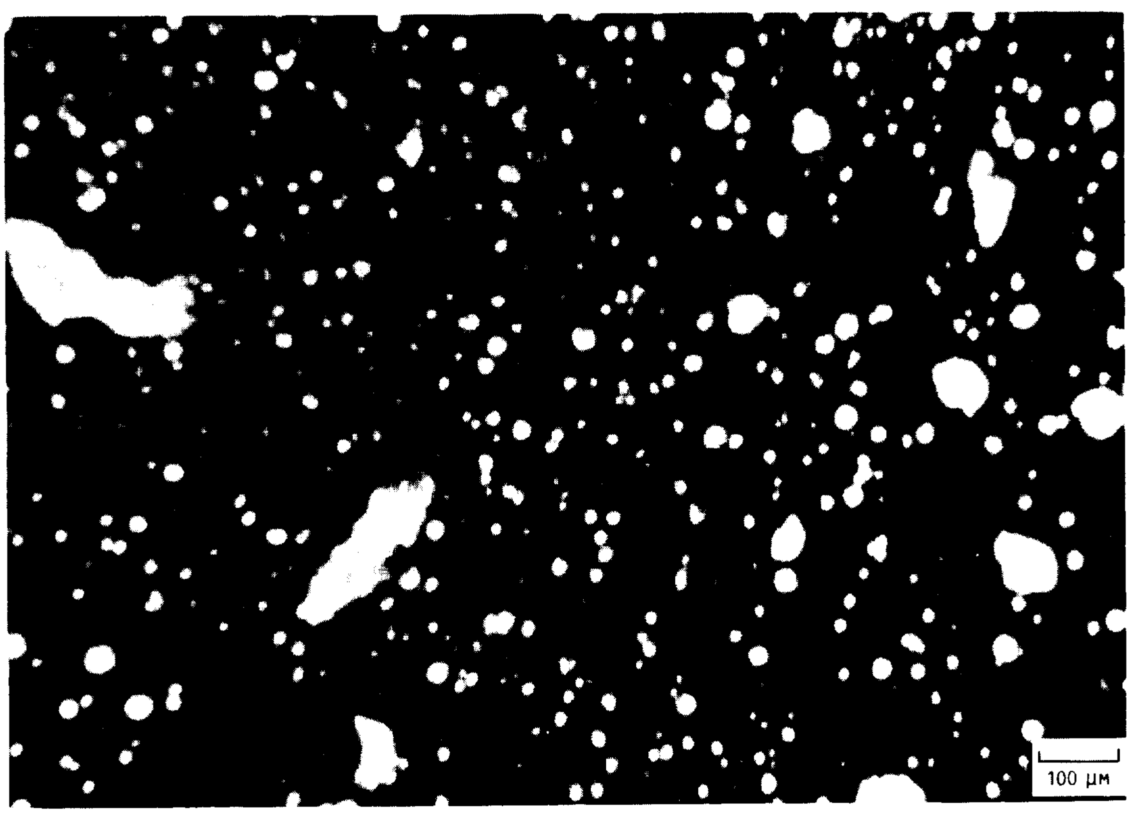


(B) TUNNEL AMBIENT TEMPERATURE - 13 ^{0}C.

FIGURE 11. - EFFECT OF TUNNEL TEMPERATURE ON SOOT SLIDE IMAGES ATOMIZING AIR CONDITIONS 646 KPA, 82 ^{0}C.



(A) ATOMIZING AIR CONDITIONS 450 kPa, 82 °C, DROPLET SIZE 12.4 μm.



(B) ATOMIZING AIR CONDITIONS 820 kPa, 110 °C, DROPLET SIZE 7.5 μm.

FIGURE 12. - SOOT SLIDE IMAGES AT AN AMBIENT TUNNEL TEMPERATURE OF - 13 °C.

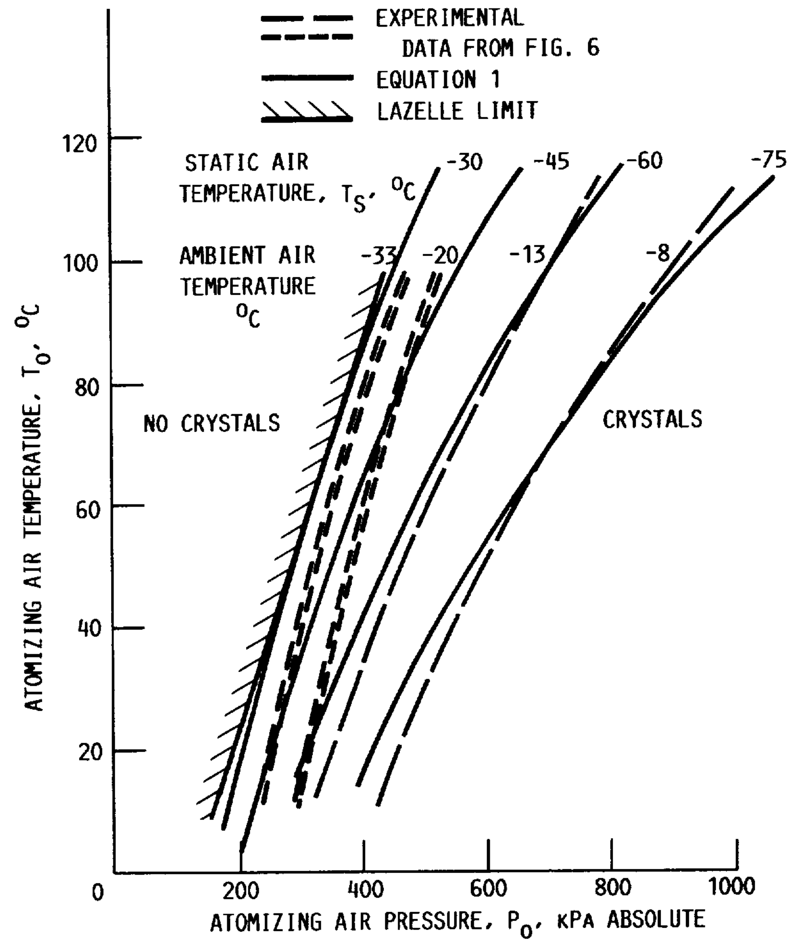


FIGURE 13. - ISENTROPIC EXPANSION LINES OF CONSTANT STATIC TEMPERATURE T_S, COMPARISON WITH DATA.

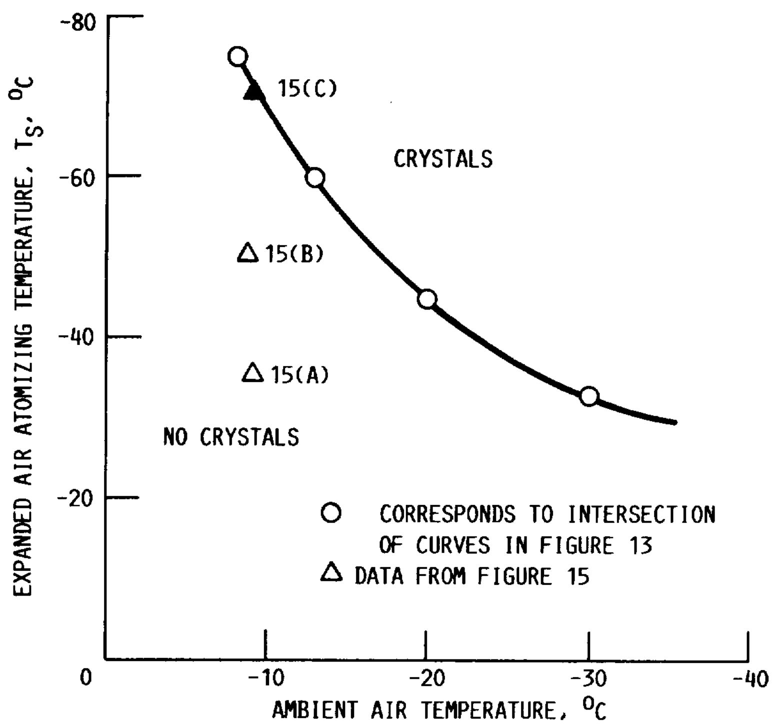
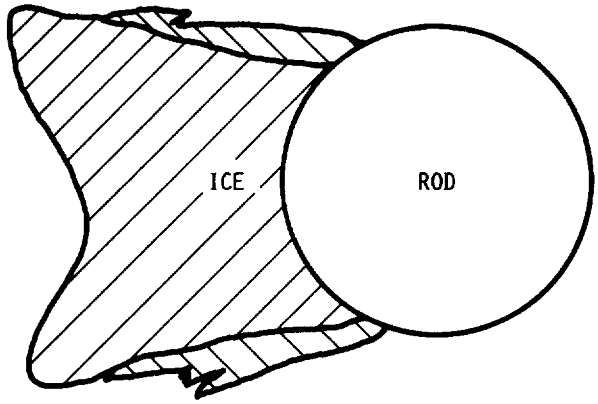
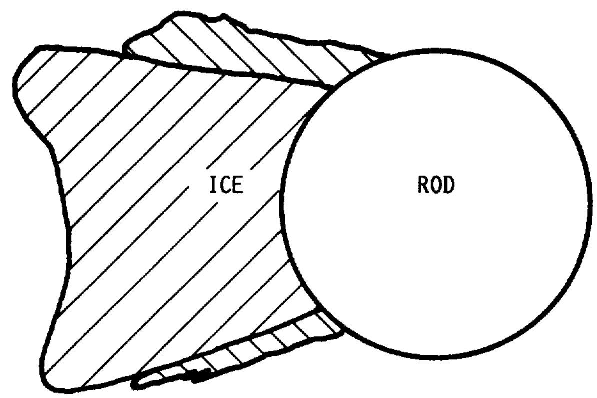


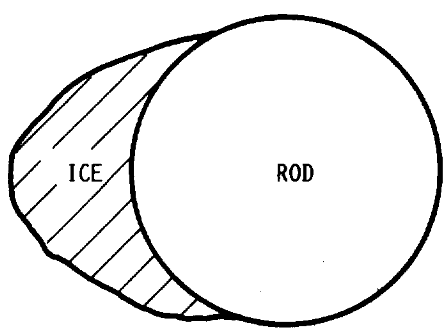
FIGURE 14. - RELATIONSHIP BETWEEN EXPANDED NOZZLE STATIC TEMPERATURE AND AMBIENT AIR TEMPERATURE TO PREVENT CRYSTALLIZATION.



(A) ATOMIZING AIR TEMPERATURE 93 $^{\circ}$C, EXPANDS TO -35 $^{\circ}$C.



(B) ATOMIZING AIR TEMPERATURE 71 $^{\circ}$C, EXPANDS TO -50 $^{\circ}$C.



(C) ATOMIZING AIR TEMPERATURE 38 $^{\circ}$C, EXPANDS TO -70 $^{\circ}$C.

FIGURE 15. - EFFECT OF ATOMIZING AIR TEMPERATURE (CRYSTALLIZATION) ON ICE SHAPE. 2.54 CM DIAMETER ROD. TUNNEL AMBIENT TEMPERATURE -9 $^{\circ}$C, ATOMIZING AIR PRESSURE 450 KPA, INITIAL WATER TEMPERATURE 38 $^{\circ}$C. LWC 0.6 G/M^3, TIME 6.0 MINUTES.

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16. Abstract

In order to produce small droplets for icing cloud simulation, high-pressure air-atomizing nozzles are used. For certain icing testing applications, median drop sizes as small as 5 mm are needed, which require air-atomizing pressures greater than 3000 kPa. Isentropic expansion of the ambient temperature atomizing air to atmospheric pressure can result in air stream temperatures of -160 °C which results in ice crystals forming in the cloud. To avoid such low temperatures, it is necessary to heat the air and water to high initial temperatures. An icing spray research program was conducted at AEDC to map the temperatures below which ice crystals form. A soot slide technique was used to determine the presence of crystals in the spray.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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